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Adaptation to sea level rise on low coral islands: Lessons from recent events

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ABSTRACT

In the past two decades there have been fears that many low-lying atoll islands around the world could disappear as a consequence of climate change and sea level rise, leading to mass migration and threatening the existence of several island nations. Here we show how sea level rise does not inevitably lead to coastal areas becoming uninhabitable, and that humans have an innate and often underestimated capacity to adapt to changes in their environment. To do so we showcase three instances of human- and earthquake-induced land subsidence that have taken place in the 21st century, where the coastal/island areas are still inhabited despite the challenge of living with higher water levels: the Tohoku coastline following the *2011 Tohoku Earthquake Tsunami* (subsidence ~0.4–1.0 m), the present day situation of coastal areas in Jakarta due to ground water extraction (> 5.0 m), and the islands of Tubigon, Bohol in central Philippines after the 2013 Bohol Earthquake (~1.0 m). Humans are able to adapt and arrive at solutions even when confronted with cases of rapid rises in water levels, and thus it is likely that in the future vulnerable coastlines will be engineered and largely remain at present day locations, particularly in densely populated areas. If anything, around densely populated areas it is more likely that humans will continue to encroach on the sea rather than the reverse. We caution, however, that small islands are not homogeneous, and many are unlikely to respond to rising sea levels in the manner that atolls do (in fact, many might just resort to build at higher elevations). Where engineering and other adaptation responses become necessary, the financial and human resource requirements may well be beyond capacity of some small islands, which could lead to impoverishment and associated challenges in many communities.

1. Recent concerns about the “drowning” of atoll islands

In recent times there has been growing concern about the possibility that atoll island states could disappear as a consequence of sea level rise (with many articles being written on the topic, such as Ives, 2016). The logic would appear rather simple, assuming that any island that is barely surfacing from the sea (the highest point in atoll islands is typically only 2 or 3 m above sea level) would likely become submerged as a consequence of the sea level rise outlined in the 5th Assessment Report of the Intergovernmental Panel on Climate Change (between 0.28 and 0.98 m by 2100, IPCC 5AR), let alone the more extreme projections set forth in recent probabilistic process-based models such

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as those by Kopp et al. (2017), or Le Bars et al. (2017). Indeed, there have already been some examples of this, such as Holland Island in Chesapeake Bay, though social factors probably played a greater role than environmental factors, as the island was abandoned long before the loss of any significant land area (Arenstam Gibbons and Nicholls, 2005). Likewise, other areas of the planet are facing rapid rates of coastal erosion due to environmental and human factors (Shibayama et al., 2013; Nguyen et al., 2014; Esteban et al., 2015a). Many of these have led to claims of resettlement of coastal communities, in spite of the reluctance to do so by the local population, and various projects by authorities to protect the coastline (Holpuch, 2016; Davenport and Robertson, 2016). Ultimately though, it appears unlikely that major investments will be made to protect peripheral low-inhabited areas.

However, such arguments often fail to realize that atolls and their islands are complex and heterogeneous physical structures (Owen et al., 2016). Atoll islands are composed of the dead and broken skeletons of corals and other calcareous organisms that dwell on the surrounding reef system (Stoddart and Steers, 1978; Perry et al., 2011). Islands accumulate through the focussing effect of waves and currents that transport skeletal sediment to nodal locations on reef surfaces (Gourlay, 1988). They have also been shown to be geomorphologically very dynamic, and change in shape and position on reef surfaces in responses to seasonal shifts in wave processes (Gourlay, 1988; Kench and Brander, 2006), extreme events (Bayliss-Smith, 1988; Kench and Brander, 2006) and sea level change (Webb and Kench, 2010; Kench et al., 2015; McLean and Kench, 2015).

Taking into account such geomorphological complexity, it becomes apparent that for the islands to survive in their present form it is necessary for them to have healthy coral and associated carbonate producing populations (Perry et al., 2011; Yamamoto and Esteban, 2014). However, pressure from human populations and episodic bleaching events due to high water temperatures (associated for example to El Niño events) are currently threatening many coral ecosystems around the planet. Biologists fear that such stresses are likely to intensify due to the warming and the increasing acidification of the oceans –brought about by the absorption of CO_2 into ocean water, which reduces the ability of corals to produce their skeletons. As a result, it is thought that within two decades coral reefs could be in severe danger throughout the world (Veron et al., 2009). If coral species do disappear from the tropical seas then a logical outcome may be that the long term survival of atolls as we presently know them would be in danger, as they would be unable to keep up with the pace of sea level rise without the continuous supply of sediments generated from reef systems.

2. Human adaptation: evidence from cases of coastal land subsidence

The authors have travelled extensively to areas affected by natural hazards in the course of their work, and have encountered three locations that can shed some light on the likely adaptation strategies that humans can use against sea level rise. Basically, in all of these locations the ground level very rapidly sank with respect to the sea level, allowing this to be used as a proxy of what would be the consequences of sea level rise in the future. These three case studies are summarised in Table 1.

The first case study concerns the *2011 Tohoku Earthquake and Tsunami*, in Japan. On the 11 March 2011 a magnitude 9.0 earthquake off the north-eastern coast of Japan triggered a tsunami that devastated coastal areas (Mori et al., 2012). Also, the earthquake caused a substantial sinking of land in Japan, and resulted in the regional lowering of the north-eastern part of the country by around 78 cm (see Fig. 1), with maximum reported values of vertical subsidence reaching up to 120 cm (as reported by the Geospatial Information Authority of Japan). Originally, much of this area was part of what is referred to as the “Rias coastline”, where the mountains reach right up to the sea and only the end section of deep valleys is inhabited (typically by fishing villages and towns, see Mikami et al., 2012). As a result of the earthquake the ground sank, and much of the coastline was barely above mean sea level, with large portions of it being flooded at high tide (see Fig. 1).

The Japanese government responded with a massive program of public works, piling up aggregates to return the coastal areas to their original levels or even increase them, and ensuring that no ground was lost to the sea (Esteban et al., 2015b). Clearly, this was possible due to the vast financial and engineering resources available to the world's 3rd biggest economy, and it must be acknowledged that resources of this magnitude are not available to most small islands, and thus would be a major constraint in those jurisdictions (Mimura et al., 2007). However, the fact that such massive land loss along over 200 km of the coastline could be reversed in a matter of a few years highlights how adapting to the much slower sea level rise that is projected to take place in the course of the 21st century is technically feasible and possible, provided there are no resource constraints. This is also the result of other recent research by Hinkel et al. (2018).

However, to illustrate what would happen if earthquake-induced land subsidence occurred in an impoverished island community, it is worth looking at the case of the islands of Tubigon, Bohol in central Philippines. After a 7.2 magnitude earthquake with its epicentre in mainland Bohol in October 2013, four nearby island communities in the Municipality of Tubigon experienced land subsidence (probably in excess of 1 m, Jamero et al., 2017) and began to suffer tidal flooding during normal high tides (see Fig. 2). Prior to the earthquake, these islands only suffered tidal flooding whenever there were strong typhoons. Direct measurements conducted in 2016 showed that the islands became completely inundated during the highest tides of the year, with median flood levels reaching up to 20.5–43 cms, and partial flooding taking place between 44 and 135 days per year (Jamero et al., 2017). Tidal flooding happens over several days around the new and full moon, and lasts for an average of 3–4 h. It may occur partially or completely throughout the entire year, depending on the tide level and local weather conditions.

Although attempts have been made by the municipality of Tubigon to relocate the communities onto the mainland, the residents have remained in the islands despite the inconvenience posed by tidal flooding, primarily due to their fishing-related livelihoods. Instead, residents

Table 1
Summary of case study sites.

Location	Geological setting	Elevation	Socio-economic setting	Cause of subsidence	Subsidence range	Response
Tohoku coastline, Japan	Rias coastline	Underwater at high tide	Peripheral region of major industrialized nation	Tectonic (earthquake)	~0.4–1.2 m (depending on area)	Elevating land throughout region
Tubingon islands, Philippines	Coral islands	Underwater at high tide	Poor fishing communities in a developing country	Tectonic (earthquake)	~1.0 m (actual value unknown)	Houses on stilts, partial elevation land
Jakarta, Indonesia	Deltaic coastline	Underwater at low tide	Slums within a major developing country capital	Groundwater extraction	> 5.0 m (currently 10–20 cm, depending on part of coastline)	Elevation of land, building dykes

Fig. 1. Left. The ground around coastal areas of Tohoku, Japan, subsided by 0.5–1.0 m. Photo taken in Ishinomaki port, 2011 during high tide.

Fig. 2. Basketball court in Ubay island, off the coast of Bohol, Philippines, during high tide. .

have rebuilt their houses by elevating the floors (using coral stones they collect from the reef flat, despite a ban on doing so by the Department of Environment and Natural Resources) or placing them on stilts (see Fig. 3, Jamero et al., 2016). It is worth noting that originally the islands were little more than sand banks (which are already at high risk of being flooded during the storm surges generated by the frequent passage of typhoons through the area), and that from the 1930s residents expanded them by piling up coral stones (Guieb, 2014; Owen, 2011). Thus, it could be said that land reclamation using coral stones has been an adaptation strategy used by local people for almost a century, though the excessive use of coral stones could deepen the reef flat and allow higher waves to be able to reach the island (Storlazzi et al., 2011). This could potentially open an "energy window" that could allow greater geomorphological change to take place (Kench and Brander, 2006), though whether this will really take place will depend on the amount of sediments produced by the corals. Generally speaking, evidence from the Solomon Islands indicates that healthy coral systems can quite quickly compensate for earthquake subsidence (Albert et al., 2017). While taking coral stones seems not to have affected the islands in the past, corals were healthier during the early and middle of the 20th century than at present, and currently the health of the reefs around the island (known as Danajon Bank) is considered to be rather degraded (Christie et al., 2006; Jamero et al., 2017). Other adaptation strategies that have been used by islanders include elevating their belongings using especially adapted furniture, elevating sections of the small pathways that traverse the islands so that people are still mobile during high tides (see Fig. 4), and collecting rainwater using water tanks (Jamero et al., 2017). Most importantly, to reduce disaster risk, the island communities have also adapted their evacuation behaviour. While prior to the earthquake they only evacuated during strong typhoons, they now also evacuate even during weaker weather systems such as tropical depressions, especially when these coincide with high tides. This showcases how different types of adaptation strategies can be employed, and while tidal flooding has redefined their new normal, islanders have easily adapted to "getting their feet wet" on regular occasions.

Finally, one of the more extreme cases of adaptation to human-induced land subsidence comes from the case of Jakarta, in Indonesia, which has been subsiding at rates of between 9.5 and 21.5 cm/year due to ground water extraction (Chaussard et al., 2013; Ng et al., 2012). As a result, a large extent of the coastal areas is now situated below sea level and suffered extensive flooding in 2007 due to abnormally high tides (Takagi et al., 2016). To adapt to this problem dykes have been built in areas such as Pluit (see Fig. 5), and some port wharfs have been

Fig. 3. House on stilts, Batasan island, off the coast of Bohol, Philippines, during high tide.

elevated (Fig. 6). It also appears that many coastal areas are being elevated throughout the city, particularly when undertaking any new construction. In fact, the overall plan seems not to be to retreat, but rather land reclamation is being proposed for luxury projects, which would expand the city towards the sea (Takagi et al., 2017). While it is clear that land subsidence poses a great challenge to Jakarta and the groundwater extraction that causes it should be stopped as soon as possible, this case also shows that it is possible to adapt to rapid rates of subsidence if there is a will, ingenuity, technological capability and financial resources. The latter two requirements would no doubt pose a considerable challenge to many small island states, though these are not unsurmountable, as will be explained in the next section.

3. Traditional human adaptation vs. modern engineering adaptation

The above examples indicate how it is possible for coastal and island populations to adapt to rising sea levels, given that even the highest sea-level rise scenarios are projected to happen at much slower rates than the case studies outlined. "Traditional" human adaptation methods are possible, as highlighted by the experiences of the islands of Tubigon, though more modern engineering approaches also exist, as shown by the cases of Japan and Indonesia. Essentially, some of the coral islands

Fig. 4. Elevated pathways along the houses. Ubay Island, off the coast of Bohol, Philippines (taken at high tide).

that exist on top of an atoll could be reinforced using sea dykes and the land behind them raised using material dredged from nearby locations, which could include sacrificing some of the other islands. Examples of this can be seen in the case of Hulhumalé in the Maldives, an artificially reclaimed island which has an elevation of around 2 m above sea level, higher than rest of the country (the capital Malé is only 1 m above sea level). Also, rubbish, particularly plastics, can be used to create landfill areas which would gradually raise the levels of some areas of the islands, and examples of this can already be seen in Isla Bilangbilangan in Tubigon. The disposal of rubbish is actually a great problem in atolls, and in the Maldives household waste is being dumped at an artificial island 7 km from the capital, gradually increasing its size (Thilafushi, which has been nicknamed “Rubbish Island”, BBC News, 2011). This is not to advocate the construction *of rubbish islands* as a general response, it is merely to highlight an approach that has been implemented in the Maldives (and indeed “rubbish islands” have been constructed elsewhere, such as the case of Odaiba or other islands in Tokyo Bay, Japan). Clearly the potential adverse consequences for the health of marine areas and their biota would need to be thoroughly investigated, before this option can be considered desirable or efficacious.

However, it is clear that raising islands through dredging and other engineering works would be expensive, and would require the rebuilding of any infrastructure already on them, and the removal and replacement of fertile topsoil. The survival of the island would rely entirely on the strength of the perimeter defence works, and would make any island where it is attempted look like present-day Malé, which is completely surrounded by concrete protective structures (sometimes referred to as the “Great Wall of Malé”, Schmetzer, 2000). As sea level increases bigger waves would reach the island, requiring the structures to be progressively reinforced (Yamamoto and Esteban, 2014). Such engineering measures are clearly feasible for middle-income countries such as the Maldives, but could prove expensive for places such as Tuvalu or Kiribati that might have to rely on Overseas Development Aid Programs, climate change Adaptation Funds or the remittances of migrants if adequate bilateral agreements can be put in place (Yamamoto and Esteban, 2016). With this, low-cost community-based adaptation measures may prove to be more feasible for countries with lesser financial resources.

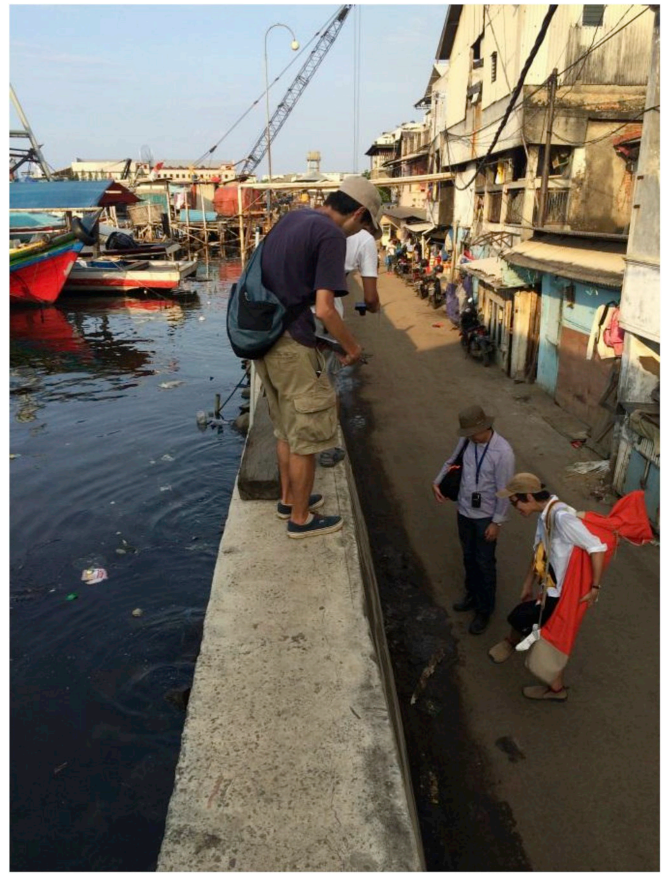

Fig. 5. Slim dyke protecting the Pluit district, Jakarta, Indonesia (taken at high tide).

Fig. 6. Elevated port wharf area in Jakarta, Indonesia (taken at high tide).

4. Conclusions

During the past decade, the authors have surveyed many low-lying coastal areas that have undergone rapid land subsidence, and can be used as a proxy to understand the types of adaptation strategies that will be undertaken by the governments and the inhabitants of densely populated coastal areas that are now faced with sea level rise. So far, the authors have found no evidence that these areas will be abandoned, and it seems that many adaptation methods are possible through modern engineering methods or human ingenuity.

However, engineering (or “hard”) adaptation comes at a cost. Relying exclusively on such measures could turn coral islands into “fortresses”, similar to that of the capital of the Maldives at present. Many beach areas would be lost, leading to the loss of tourism income, and it would be much better for atoll islands to rely on “soft”

adaptation, including improved planning options that are underpinned by better understanding of physical island change within island states (McLean and Kench, 2015; Kench et al., 2018). In particular, construction of houses on stilts and allowing coral reefs to continue to slowly build up the sand that makes these islands would be preferred to the use of massive concrete seawalls. Corals, if given enough time, will likely adapt to changing climate conditions, and some evidence already points to this (Yamano et al., 2011; Hume et al., 2016). Also, it is not inconceivable that genetically altered coral species –or the symbiotic algae on which they rely- could be developed in the future. In a sense, this would represent a “forced human evolution” of the species, which would in essence be in line with the idea of the “Anthropocene”, where the actions of humans are the main drivers on the physical environment. If such measures fail, beach nourishment, sacrificing some smaller islands or deepening the lagoons inside the atolls, could also gradually contribute to the build up of the islands.

Atolls, if not all coral islands, have considerable morphological resilience, and it is unlikely that they would disappear any time soon, even if the worst predictions of mass coral mortality and sea level rise are realized, as shown by the evidence provided from the islands of Tubigon, Bohol in central Philippines. It should be pointed out that many of the geomorphological characteristics of coral islands are unique, and thus the views of the authors are not necessarily applicable to other islands around the planet (for example, the presence of a hard shallow reef-flat” which would be different from small islands in river deltas).

Nevertheless, all of these adaptation measures will probably come at a cost, and the authors think that it would be far better to undertake mitigation strategies that would slow down the pace and severity of sea level rise and climate change, as adapting will likely impose extra financial, human and ecological burdens on areas of the planet that are generally less well off. Thus, rather than focussing on mass migration, which has currently become the centre of climate change discourses, policy-makers around the world should exert a greater effort in creating and implementing effective mitigation strategies, in line with the objectives of the United Nations framework Convention on Climate Change. In the meantime, there is an opportunity for scientists working collaboratively with affected communities and other stakeholders to explore and develop more efficacious adaptation strategies that are cost-effective, environmentally friendly and culturally acceptable.

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